CONTROL STRATEGIES OF DIGITAL REPRODUCTION WITH A VIEW TO PRINT QUALITY

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ABSTRACT

Digital pre-press control of originals for printing is discussed from the aspects of data flow, information transfer and original-to-print fidelity. The choice of screening parameters and the adjustment of tone and detail rendering are explored. A control strategy is presented and its implementation in a laboratory scale digital picture processing system is outlined. According to the results obtained, image quality in printing can be significantly enhanced by utilization of a combination of information transfer and fidelity criteria in reproduction control.

INTRODUCTION

In the control of a reproduction process it is practical to perform all operations for image quality adjustment in pre-press processing and to maintain the subsequent process steps constant. Image processing can be carried out on an optical signal in a reproduction camera, on an analog signal in a scanner or on a digitized signal in a computer. Current practice is to base the control on the characteristic curve or overall tone rendering curve of the process. Visual evaluation and highly skilled craftmanship are still required to a large extent.

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In camera or analog scanner work using a contact screen, the adjustability of control operations is limited by the performance of reproduction photography with respect to image formation /26/. Digital picture processing does not suffer from this drawback; the characteristic curves can be replaced by mathematical process models at will. However, due to several aspects of reproduction quality, efficient pre-press picture processing requires mathematical formulation of the platemaking and printing processes. This presents a new challenge.

The throughput of any digital control operation to the final print is limited by the level of performance of the subsequent processes. With the increased automation of printing, the performance level is continuosly improving and variations are decreasing.

It is evident from the foregoing that both digital reproduction and printing automation motivate a quality analysis in pre-press picture reproduction. In this work, digital reproduction is discussed with particular emphasis on the significance of the performance level of printing. The aim is to pinpoint the most important performance characteristics of offset printing and to show how they influence pre-press control. The studies to be reported were performed in connection with system development work for digital processing of one-colour pictures.

Image quality is ultimately a subjective property. However, the range of subjective quality assessment is governed by objectively quantifiable models of human vision. Some relevant aspects of human visual perception are considered.

Quality adjustment operations can be carried out by means of automatic or interactive control. The former is based on a predetermined or an adaptive control model. The parameters of the model can be constant or computed by the control system from image data. In interactive control, the operator chooses the desired control in an iteractive manner by modifying the image on display and evaluating the result. The discussion in this paper is directed to automatic control.

Control of digital picture reproduction is divided into two parts,

- selection of the values of the process variables and
- adjustment of originals for printing.

Process variables include sampling and screening parameters. These have to be chosen for every platemaking and paper-ink-press combination. In adjustment operations, the originals are fitted into the printing process for the achievement of as high and even a degree of quality as possible.

IMAGE QUALITY

Objective image quality of one-colour pictures can be defined in terms of three types of properties /20/,/Fig. 1/. The gamuts or spaces of tone and frequency, and uncontrolled density variations called noise are expressions of the performance of the process including materials. The second property, fidelity, characterizes the similarity of a printed image with the original image or object. It is determined by the pre-press adjustment operations within the limits of process performance. The concept of image information has two facets. Transfer of statistical information to the print expresses the original-print similarity in a relative

GAMUT	— tone space — frequency space — noise	performance limits
FIDELITY	— tone rendering — detail rendering	optimization by control
INFORMATION	— statistical information — semantic information	optimization by control

Fig. 1   Image quality components.

sense. Semantic information is related to the visibility of forms and shapes in the image, and could thus be called intelligent information.

Subjective assessment of image quality is of necessity based on objectively measurable image properties. However, the relative significance of the different properties is known to be dependent on image content /6,7,18 /, subjective preferences /16/ and the purpose of viewing /9/. For this reason the relationship between subjective and objective image quality cannot be expressed exactly. If only the role of the reproduction process is considered, the situation simplifies somewhat and the relationship can be presented schematically as shown in Fig. 2. At very low

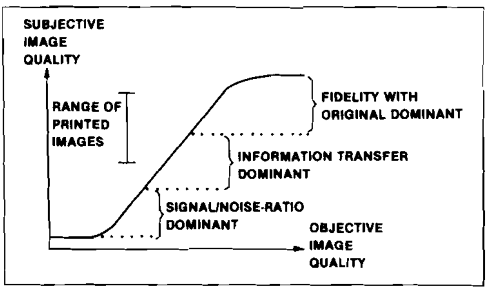


Fig. 2. Relation between objective and subjective image quality.

levels of quality, detection of the image is limited by noise, and consequently the signal-to-noise ratio represents a critical quality component. At higher levels of quality, transfer of information from the original image gains more importance. With further increase in the quality level, input-output fidelity of tone and detail reproduction becomes the most important objectively measurable quality component as far as subjective quality is concerned. Printing processes operate in the region in which either information transfer or fidelity has dominating importance. However, in the field of newspaper printing, overall printed product quality has recently, been expressed in terms of a combined signal-to-noise ratio /22/.

At still higher quality levels than those discussed above, the human visual system is no more capable of responding to variations in objectively measured quality, and the relationship between objective and subjective quality ceases to exist. As far as detail reproduction is concerned photographs of good image quality fall into this range.

INFORMATION FLOW

In digital reproduction, there are two aspects of information flow. Firstly, choice of the levels for the process variables determines the magnitude of data flow through the digital reproduction and the information efficiency of the process. Secondly, the transfer of information from an original image to the print can be influenced by image processing.

The relevant process variables in a digital pre-press system include

-picture element (pel) size
-halftone dot matrix size or screen ruling

-the number of grey levels and
-the halftone dot structure used.

Pel size is subjectively the most critical variable in line drawings. The modulation transfer function of the human visual system implies that a pel size of the order of 20x20...25x25 $/um^2$ (depending on viewing distance) is sufficient /7/. In newspaper printing conditions a pel size of 30x30 /um was experimentally found to be small enough /28/. The estimate above quoted, calculated on the basis of the MTF of the visual system, is rather low. This is by reason of the fact that the visual MTF does not, of course, take into account the MTF of the printing process which acts by reducing pel visibility. The estimate can be suuposed to be representative of high quality printing, in which contrast loss is relatively minor. The capacity of a process to print small dots can be estimated from the MTF or is given directly by its Fourier transformation, the point spread function (PSF). Typical values are given in Table 1.

Table 1 Performance of two types of offset printing processes

	density range	rms noise	information capacity	tones in print	information efficiency	frequency range x)	limiting dot size
	D	D	bits/cycle			mm^{-1}	µm
"newspaper"	<1	0,04 - 0,08	~ 5,5	<= 40	~ 0,50	5	25
"coated"	<2	0,02 - 0,04	~ 6,5	<= 100	~ 0,65	12	10

x) MTF is modelled as $M = a\ e^{-bf}$

"newsprint": a=1,03, b=0,105, r=0,998, n=21
"coated": a=1,00, b=0,044, r=0,999, n=21
Frequency range computed at MTF level 0,6
Limiting dot size determined by the PSF

The choice of screen ruling for production printing is at present based on test printings. Too fine a screen becomes filled in, whereas too coarse a screen gives poor detail rendering and individual halftone dots may be visible /19/. Digital processing allows more freedom in the utilization of exact criteria than does optical or analog processing. Some aspects of information flow and human vision are discussed below with regard to the choice of screening parameters.

Data flow in digital screening is determined by the number of grey levels (k) and the screen frequency (f_s):

$$h_d = f_s^2 \log_2 k \qquad (1)$$

The number of outcoming density levels in printing at a given screen frequency and halftone dot structure can be computed from the signal-to-noise ratio at different halftone dot percentages /21,31/ as

$$k_p = 1 + \int_0^{D_s} D(f_s)/N(f_s)\,dD \qquad (2)$$

With the knowledge of k_p, the information capacity of prints is obtained as bits per unit area /Table 1/ from

$$h_p = f_s^2 \log_2 k_p. \qquad (3$$

Ideally, the number of grey levels reproduced in the print is at least of the same magnitude as the number of grey levels which the visual system can detect /5/ at the relevant frequency. Because of the limited printing performance, the halftone dot structure which produces the greatest number of output levels is the most applicable. However, if the process is not capable of producing as many tone levels as can be detected, the above stated criterion does not provide a sufficient condition for optimum screen ruling /Fig. 3/.

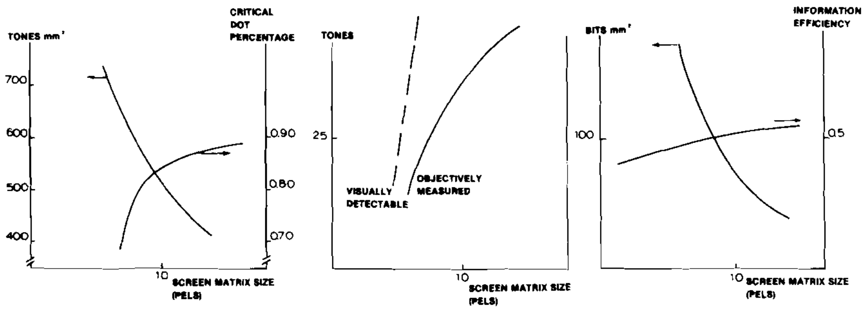
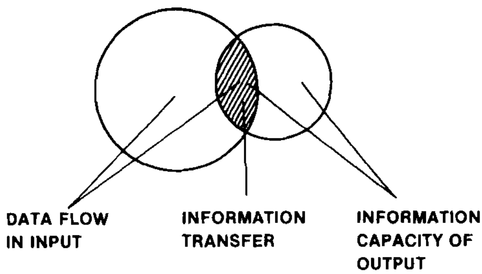


Fig. 3. Possible criteria for optimum screen ruling.

Another criterion is needed. In principle this could be related to

- the information capacity of prints
- information efficiency of the process
- number of reproduced tones per unit area or
- the tone rendering curve.

Information efficiency /12/ expresses the fraction of "correct" information of the data flow formed by the input tones. The definition is given in Fig. 4. A tone rendering criterion is



$$\text{INFORMATION EFFICIENCY} = \frac{\text{INFORMATION TRANSFER}}{\text{DATA FLOW IN INPUT}}$$

Fig. 4 Definition of information efficiency.

usually employed. The logic is as follows. In printing, filling-in of dark halftones should be shifted to as large dot percentages as possible. This is because filling-in causes steepening of the tone rendering curve, with two consequences. Firstly, the printing process becomes unstable and sensitive to disturbances. Secondly, the information transfer characteristics of the process suffer /See Appendix/. For these reasons it is reasonable to require that filling-in sets in only above a given halftone dot percentage. This condition is then used as the necessary additional criterion for definition of the range of optimum screen rulings. Two examples of optimum screening ruling ranges are given in Table 2 as calculated from experimental data with the requirement that a 90 % halftone dot must not fill-in. The halftone dot structure is diamond-shaped, which is close to the optimum with respect to the number of outcoming density levels.

Table 2 Estimated ranges for digital reproduction parameters in offset printing conditions

	S/N solid	min pel µm	screen ruling cm^{-1}	number of input tones
"newspaper"	10 ... 25	25 ... 35	25 ... 35	64 ... 128
"coated"	50 ... 100	10 ... 15	35 ... 75	128 ... 256

RESTORATION AND ENHANCEMENT

The objectives of pre-press quality control are:

- correction of faults appearing in originals
- compensation of variations occurring between originals
- advance compensation of the distortions occurring in platemaking and printing
- intentional distortion of image properties for better visual appearance.

The first three objectives on the list are by nature restoration operations, while the last is typical enhancement, by which information transfer - both statistical and semantic - is accentuated. When a control operation acts by modifying an existing property in an original it is a posteriori operation. Conversely, processing an image with a view to subsequent quality alterations in platemaking or printing, or with consideration of visual perception, is characteristically a priori by nature. The criteria of processing fall into the classes of better objective or subjective fidelity or information transfer.

Tone rendering is a typical fidelity measure. According to current practice, the top and bottom densities of originals are adjusted so as not to vary from one original to another in print. In camera reproduction the differences between originals are equalized by using either auxiliary exposures or multiemulsion films. Control is based on manual density measurements made from each original. However, tone rendering is inadvertently distorted along with the density range modification /26/. Tone rendering can be adjusted by similar methods within the limits of the characteristic curves of the materials. A point by point control is not possible. The shape of the tone rendering curve has been the subject of lively discussion in the literature /2,3,13,33,35/.

Digital control of tone rendering can combine several purposes in a versatile manner, because a digitally stored image can be modified by computations virtually as desired. A prerequisite is, of course, that the control model is known. Linear extension of the density range of the original over the dynamic range in digital processing can be automatically accomplished. The same applies to any predetermined tone rendering model. Digital processing, offers more options as regards equalization of tone rendering variations between originals.

Transfer of statistical information from the original to the print is maximized by maximization of the average mutual information I(g;f) between the input and the output

$$I(g;f) = \iint p_f \, p_{g/f} \log_2 (p_{g/f}/p_g) \, df \, dg. \qquad (4)$$

Assuming additive noise, mutual information is maximized when the input image is transformed in such a way as to give rise to an even probability distribution of tones, i.e. an equalized histogram, in the output (see Appendix). Fig. 5

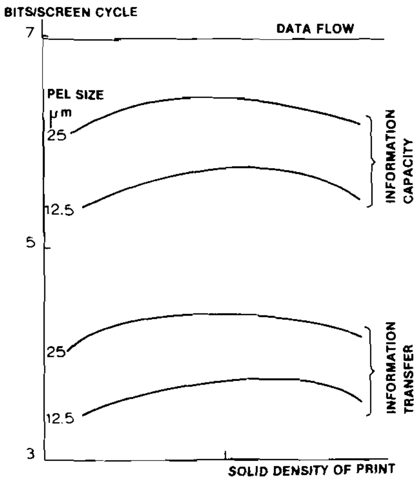


Fig. 5 Loss of information in printing.

illustrates how input data flow /Formula (1)/ is reproduced in printing. This represents the situation in which the input histogram is even, i.e. it characterizes the rendering of the input grey levels in the print. The information loss /32/ evident in Fig. 5 arises on the one hand from the limited tone rendering capability of the printing process (newspaper printing) and on the other hand from noise.

Modification of the shape of the histogram /1,10,11,23/ offers a powerful tool for tone rendering adjustment. As indicated above, equalization of the histogram

$$g = \int_0^f g_{max}\, p_f(f)\, df \qquad (5)$$

produces an image in which the relative image area of every density level is the same. This is obtained by expanding the density range covered by the density bands having frequent occurrence in the original.. Fig. 6 illustrates a typical influence of histogram equalization in comparison with other schemes of tone rendering.

When histogram equalization is applied to originals which differ with respect to top and bottom densities or average density levels, these differences become eliminated. Histogram equalization also produces some improvement in detail rendering. A considerable advantage of histogram equalization is that it can be performed completely automatically.

Tone rendering can be intentionally distorted by histogram modification. The magnitude of distortion is dependent on the initial deviation of the histogram in question from an even distribution. If the original is of good quality, the distortion may impair fidelity beyond visual acceptance and be more disturbing than variation in the tonal level between the printed originals. In fact in the case of a good quality original there is little need for tonal adjustments by histogram modification converse to the situation in the case of a poor quality original. This situation has led to the development of interactive tone rendering adjustment schemes /4,17,34/.

In automatic control a balance must be found between preservation of original-to-print fidelity on othe one hand and information transfer on the other. It is obvious from Fig. 2 that in high quality printing the fidelity aspects should be weighted while information transfer considerations gain more significance when the performance of the printing process is on a low level. The effect on quality of equal weighting of histogram equalization and constant linear tone rendering in the control model is shown in Fig. 6 and Fig. 7.

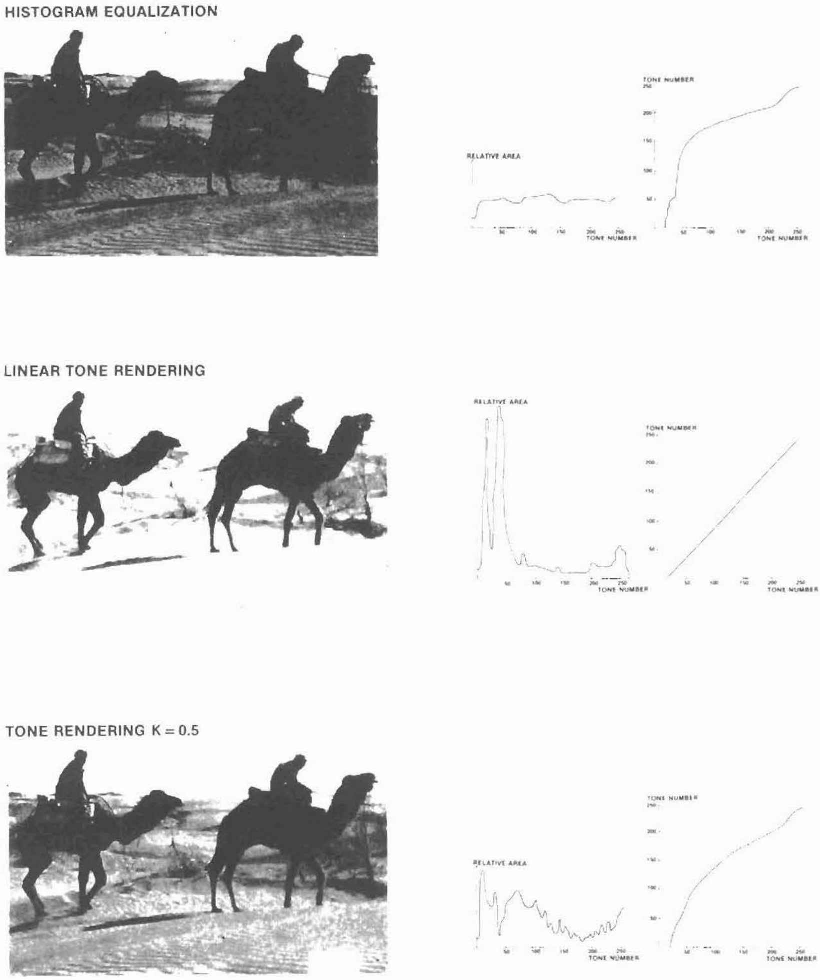


Fig. 6 Influence of tone rendering adjustment on image quality.

A basic question related to a priori tone rendering compensation of printing is how the tone rendering curve, i.e. the relationship between halftone dot area in the digitized screened input and integrated density in the printed output, is formed. Quantitative knowledge of this relationship is required for accurate control of digital reproduction for the achievement of a desired result in the print.

The classical formula for the relationship between relative halftone area and integrated density /36/

$$D_{int} = -n\ \lg(1 - A + A10^{-D_s/n}) \qquad (6)$$

does not include the known influence of spatial frequency /25,27/ and gives a rather inaccurate prediction of integrated density. The influence of frequency is included by modification of the reflectance profile of a halftone dot by the point spread function of the process /27/:

$$D_{int} = -\lg\ c^{-2} \iint^{c} 10^{-f(x,y)*h(x,y)}\,dxdy \qquad (7)$$

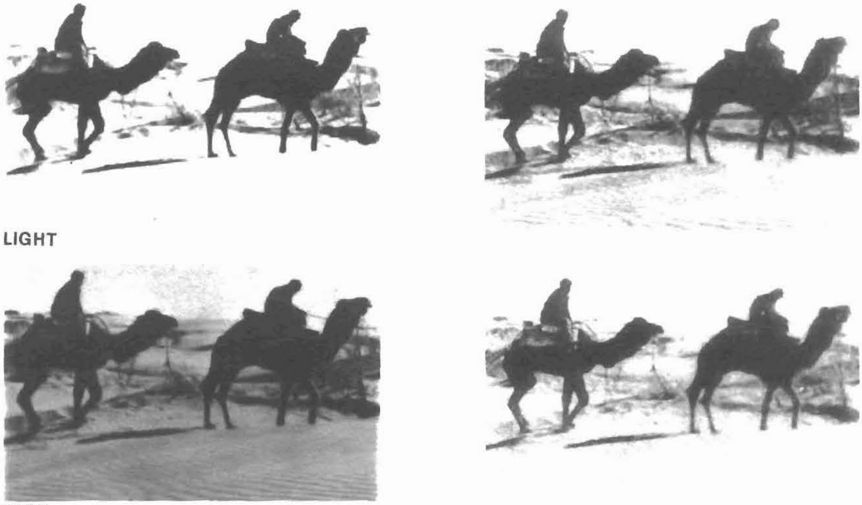


Fig. 7 Influence of balancing of histogram equalization and constant linear tone rendering on image quality in the case of originals of different average density level. Originals left, prints right.

According to measurements made in this work, a good approximation for integrated density can be computed by neglecting the density profiles of individual dots but including the variation of two-dimensional modulation transfer with frequenbcy. The simplification allows Formula (7) to be reduced to

$$D_{int} = - \lg \left(A \operatorname{antilog}(-D_{max}(A+M_1-M_1A)) + (1-A)\operatorname{antilog}(-D_{max}(A-M_2A)) \right) \quad (8)$$

M being modulation transfer factor. The subscripts 1 and 2 refer to frequencies of and between the dots respectively. The MTF of an offset printing process can be successfully modelled as

$$M = a\ e^{-bf}. \qquad (9)$$

Consequently, M_1 and M_2 obtain the following forms:

$$M_1 = a\ e^{-bf(1/2d)}$$
$$M_2 = a\ e^{-bf(1/2(c-d))} \qquad (10)$$

A priori compensation of tone distortion in printing involves processing of image data with the inverse of the tone rendering curve in printing /Formula (7)/. Once the latter is known, processing can be effected automatically.

The correction of spatial faults in originals, such as graininess, unsharpness and local blur can be accomplished with several digital methods /23/. With the exception of oversize enlargements and telephoto pictures, the spatial resolution of photographs used as originals is, however, generally much better than that of printing /19,20/. For this reason correction of originals with regard to image distortions arising in photography is as a rule unnecessary. Conversely, enhancement type control of detail rendering may be rewarding. Such processing acts by boosting the transfer of semantic information. Fig. 8 shows examples of the influence of automatic detail enhancement on image appearance in newspaper printing conditions

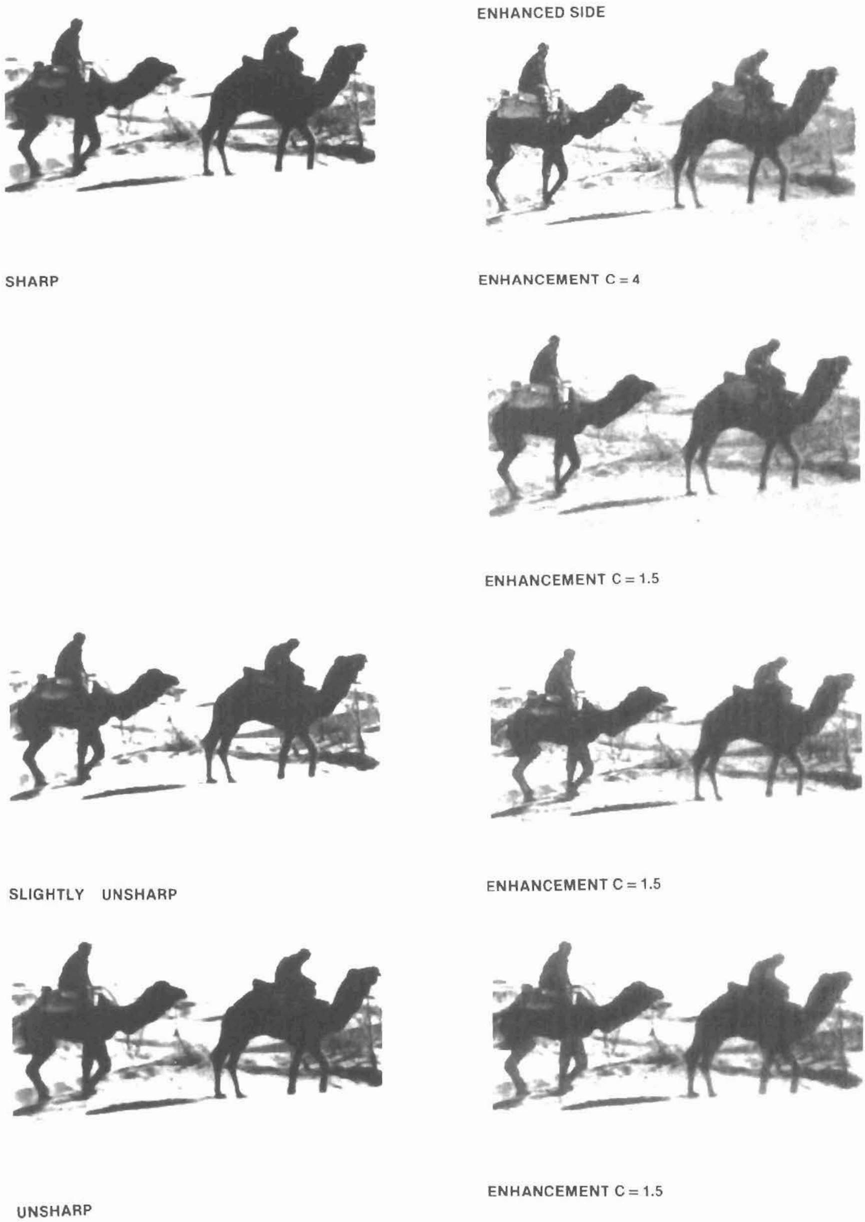


Fig. 8 Influence of detail enhancement on image quality in the case of originals of varying sharpness. Originals left, prints right.

The conditions for "optimum" detail enhancement still remain to be defined. It seems possible that the visual impact of detail enhancement is related to both image subject (autocorrelation function) and tone rendering /6,8/. The level of noise in the image also appears to play a part. Despite these complications there is no doubt of the benefits of an automatic detail enhancement model. For the maintenance of the quality level customary in conventional reproduction, detail enhancement may even be highly necessary. This is because the natural detail enhancement of halftone photography - as caused by adjacency effects - is lost.

CONTROL STRATEGY

Control of pre-press reproduction consists of four parts

-data flow
-information transfer
-a posteriori fidelity control and
-a priori fidelity control.

An overall control scheme is shown in Fig. 9. The parameters governing data flow are partly fixed for a given digital reproduction process installation. To the extent to which they are variable, the parameters are chosen on the basis of knowledge of platemaking and printing conditions. The balance between information transfer and fidelity aspects is chosen separately for every picture using knowledge of the properties of the picture and the platemaking and printing conditions.

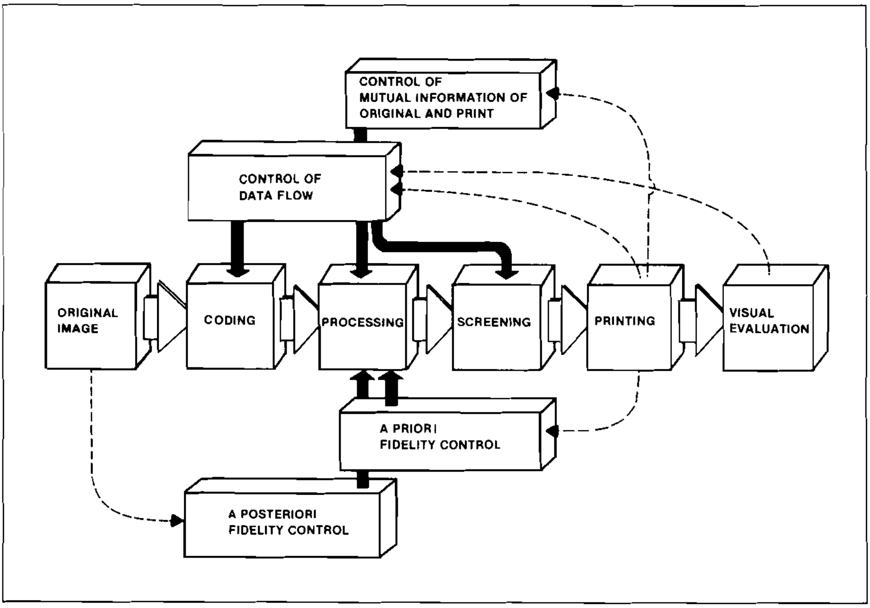


Fig. 9 An overall control scheme of quality in digital reproduction.

A flow diagram of the control system, in the form in which it has been implemented, is presented in Fig. 10. The system consists of three independent adjustment blocks. First, control of tone rendering is performed. Any constant tone rendering curve can be applied, or alteratively the histogram equalized, or any selected combination of these two may be chosen. In the second block (s^{-1}) tone rendering distortion of platemaking and printing is compensated. The third block computes the detail enhancement by utilization of digital homomorphic filtering. Either low-pass or high-pass filtering can be chosen, according to the selection of the enhancement parameter (in Fig.10).

Tone rendering and detail rendering can operate automatically or interactively. In automatic operation, the values of the control parameters as well as of the control models are prefixed. This is always the case in platemaking and printing. In the development of the system, it has been advantageous that a monitor (Comtal Visual One display system) has been available for visual assessment of the control result.

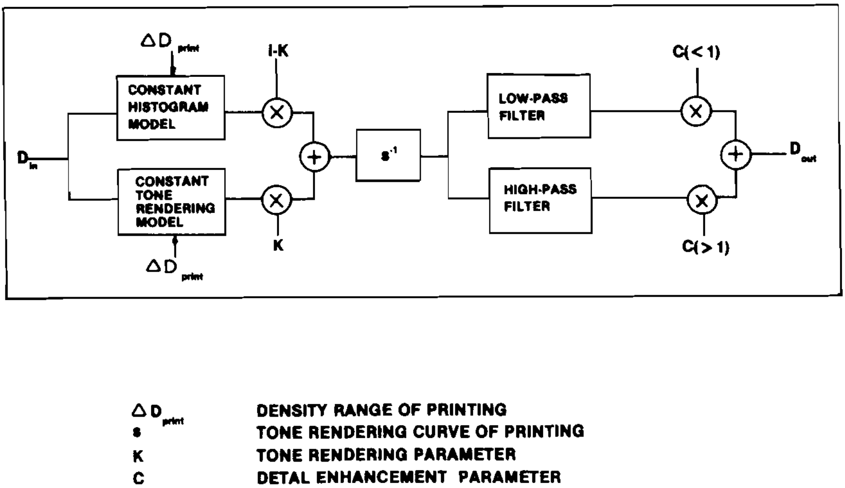


Fig. 10 A control model as implemented in a laboratory scale picture processing system.

A digital quality control system as outlined above was programmed into a laboratory scale image processing system consisting of a DEC PDP 11/34 minicomputer, a CDC 300 MB disc memory and optronics scanners as I/O devices. With this system, halftone films can be produced from reflection or transmission originals. After copying on aluminum offset plates printing has been effected in these experiments on offset presses.

CONCLUSIONS

The increasing application of digital pre-press picture reproduction has given rise to new challenges and introduced new requirements, not least with regard to the control of image quality. Because of more degrees of freedom in quality adjustment, there is a need for more detailed understanding of the nature of printed image quality than has hither to been available. The considerations presented in this paper support the hypothesis that data flow, information transfer and image fidelity as aspects of quality can be combined in pre-press reproduction control for quality improvement. A suitable balance between the two latter parameters also eliminates quality fluctuations between originals.

The outcome of any control operation in the print is subjected to the distortion which occurs in the platemaking and printing processes. Compensation of the distortions requires mathematical formulation of the performance characteristics of these processes. Such modelling was found to be possible and could be successfully utilized in a automatic digital control scheme.

SYMBOLS

a,b	parameters in the model for the MTF of printing /Formula (9)/
c	halftone period
d	halftone dot diameter
e	base of natural logarithm
f	spatial frequency
f( )	input density function
f_s	screen frequency
f	processed input image
g(	output density function
h( )	point spread function
h_d	data flow in screening
h_p	information capacity of prints
k	number of grey levels in input
k_p	number of grey levels in output
n	number of samples
p_f	input histogram

p_g	output histogram
r	correlation coefficient
s( )	process model of platemaking and printing
x( )	pre-press control model
x,y	spatial coordinates
A	relative halftone dot area
D	density
D_s	solid density
H_f	input entropy
H_g	output entropy
H_n	noise entropy
N	rms noise
M	modulation transfer

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APPENDIX

Output entropy (H_g) is defined as the average value of self information /7/

$$H_g = \int p_g \log 2 p_g \, dg. \qquad (A1)$$

Output entropy is maximized when each output density level g has equal probability. The resulting entropy value represents the information capacity of the output.

In a process /Fig. A1/ consisting of pre-

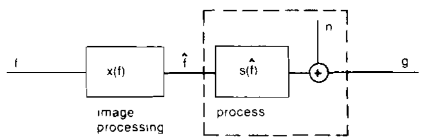

Fig. A1 A block diagram of a reproduction model

press operations x(f) and platemaking and printing processes characterized by s(f), output entropy can be expressed in terms of input entropy, the process characteristic curves and noise. Assuming statistical independence of signal and noise and writing

$$p_g \, dg = p_f \, df \qquad (A2)$$

it is obtained that

$$H_g = H_f + H_n + p f \log_2 (d \left\{ s \left[x(f) \right] \right\} df \; df. \quad (A3)$$

Correspondingly, the formula for average mutual information can be expressed as

$$I(g;f) = H_f - H_n + p f \log_2 d \left\{ s \left[x(f) \right] \right\} df \; df. \quad (A4)$$

Inserting Formula (A3) into (A4) results in

$$I(g;f) = H_g - 2H_n. \quad (A5)$$

This has the implication that under the assumptions made, maximization of output entropy maximizes the information transfer.